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TECHNICAL REPORT ECOM-0209-1

GUNN EFFECT DEVICES

QUARTERLY REPORT NO. 1

By

J. BARRERA

JUNE 1968

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND • FORT MONMOUTH, N.J.

CONTRACT DAAB07-68-C-0209 - ARPA Order No. 692
HEWLETT-PACKARD COMPANY
HEWLETT-PACKARD LABORATORIES
Palo Alto, California

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GUNN EFFECT DEVICES

QUARTERLY REPORT
15 December 1967 to 15 March 1968
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Report No. 1

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Prepared by

J. Barrera

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for

U. S. Army Electronics Command, Fort Monmouth, New Jersey

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SUMMARY

This report contains results obtained during the final months of work on Contract No. DA28-043 AMC-01758(E) and for the first month of work on Contract No. DAAB07-68-C-0209.

The former work involved the design and fabrication of CW Gunn effect oscillators in the range from 4 to 13 GHz and with output powers greater than 25 mw. By solving the GaAs material problem with solution epitaxy, the CW device investigation led to the fabrication of samples oscillating in the range 4 to 13 GHz with outputs up to 140 mw with over 5% efficiency and with maximum sample temperatures of about 1[illegible]0°C. The FM noise is qualitatively correlated to the sample current noise and is typically less than 45 Hz at 10 KHz from the carrier in a bandwidth of 200 Hz for Q's $\approx$ 200 ($\approx$ 50 db carrier power to noise power ratio).

The latter contract involves the study of high power, high duty factor pulsed Gunn effect devices. A listing is given of pertinent design requirements and the various problems that will be considered. The initial approach to the problems is outlined and a design calculation given. The schematic of a very simple pulse amplifier using RCA overlay transistors is shown along with output data of 10 amp, 1 μsec pulses and voltage pulses across both Gunn oscillator and resistor loads.

FOREWORD

The work reported in this quarterly report will consist mainly of the latest progress on the development of a CW Gunn effect oscillator and the preliminary work done on the development of a pulsed oscillator for phased array radar. The CW work is being continued as an in-house project, but the work reported here was done under the now terminated Contract No. DA28-043 AMC-01758(E) under the authorization of Contracting Officer Mr. Edgar D. Fitzgerald.

Pulsed oscillator work is being done under a new contract, No. DAAB07-68-C-0209, by authorization of Contracting Officer Captain Suzanne M. Perkins, Procurement Division, United States Army Electronics Command, Fort Monmouth, New Jersey.

The work has been performed at Hewlett-Packard Laboratories under the supervision of M. M. Atalla. The report has been prepared by J. Barrera. Significant contributions during the report period have been made by G. W. Mathers, J. Raymond, B. Farrell, and T. Fortier. Discussions with M. M. Atalla and C. F. Quate were of great benefit.

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I. CW OSCILLATOR WORK

I.1 General Observations

With the advent of excellent quality solution grown GaAs with low doping profile we have been able to concentrate on CW device design. Our objective has been to develop microwave sources with good output power over a wide band and with low FM noise. In the past few months we have succeeded in producing devices which oscillate in the range from 4 to 13 GHz and with desired output powers of from 20 to 140 milliwatts. The efficiencies are at a level of from 3 to over 5%, the operating average temperature of the devices is at a comfortable level of approximately 130°C or less, and the FM noise is well in line with that reported in previous reports.

We have found that to operate satisfactorily on a CW basis, the device geometry must be kept under careful control. The length of a device, for example, will dictate to a large extent the maximum frequency where usable power can be obtained. The reason for this is partly due to the control length has over the temperature of the device. With rising temperature there is a degradation of carrier mobility and a corresponding loss of power output at the high frequency point of operation. The effect of heat can be plainly seen in Figure 1. We have plotted maximum power output as a function of frequency for the same device biased at twice threshold, both CW and pulsed (1 μsec pulse at 1% D.F.). The device is relatively long (18.6 μm) and has a 3 db power corner at 7.6 GHz for CW operation but an 8.6 GHz corner for pulsed operation. This separation is typical as is a 3 db difference in power level between CW and pulsed devices in their

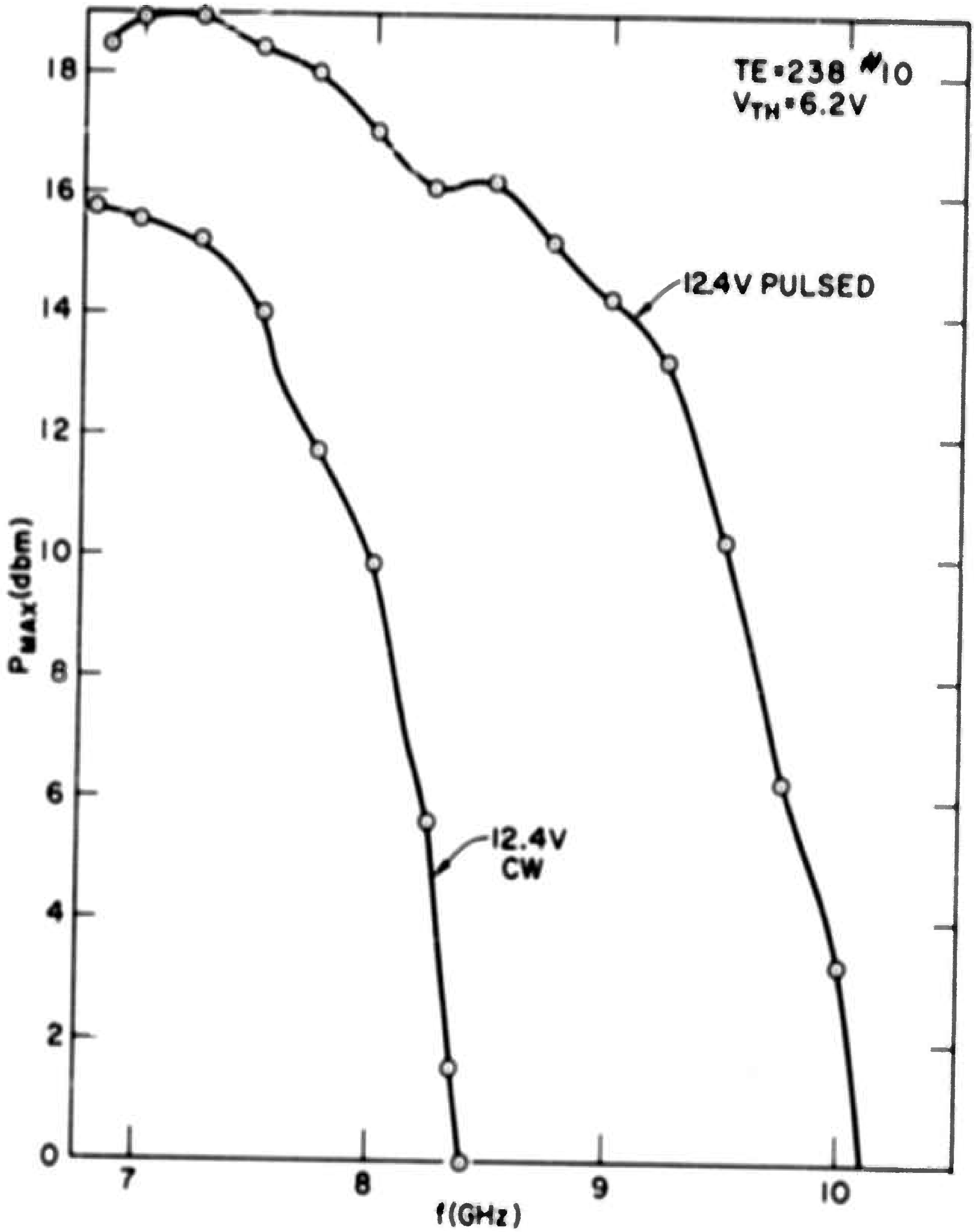

Figure 1. Pulsed and CW power output at fixed bias voltage.

power "pass band": an 18.6 μm device will have essentially constant power out from 7.6 GHz down to at least 4 GHz.

A rather apparent problem is the extremely rapid fall-off in output power for even pulsed operation. This effect is quite typical regardless of device length and is accordingly not simply a function of heat and length alone, that is, for the range of parameters that are dealt with in our CW devices, the rapid power fall-off is always present and is obviously much more rapid than the $1/f^2$ dependence expected for a domain device. Considering the fact that all our devices have nl products from 1×10^{12} cm^{-2} to usually no greater than 3×10^{12} cm^{-2}, it is suspected that our mode of operation is a very complicated one and might conceivably involve a charge buildup transient that occurs in times not much shorter than our RF frequency periods. This is not to say that a "Gunn frequency" does not exist for our samples but that depending on the magnitude of nl, the applied cavity RF voltage and the cavity loading, we can have quite different operation. In Figure 2 we show a fairly typical voltage tuning plot for various cavity lengths. The cavity is a tunable ridge guide, and the device is oscillating under very light loading in a $\lambda/2$ mode. Depending upon the initial frequency, one can voltage tune the device up to a certain voltage and then the frequency will hop down to a lower value. The locus obtained is essentially what one would expect for a true domain device. When the device has been forced into this lower frequency operation, the cavity length can be changed over a wide range with very little frequency shift occurring. The oscillation is usually very weak and is sometimes just a noise peak. It appears that we

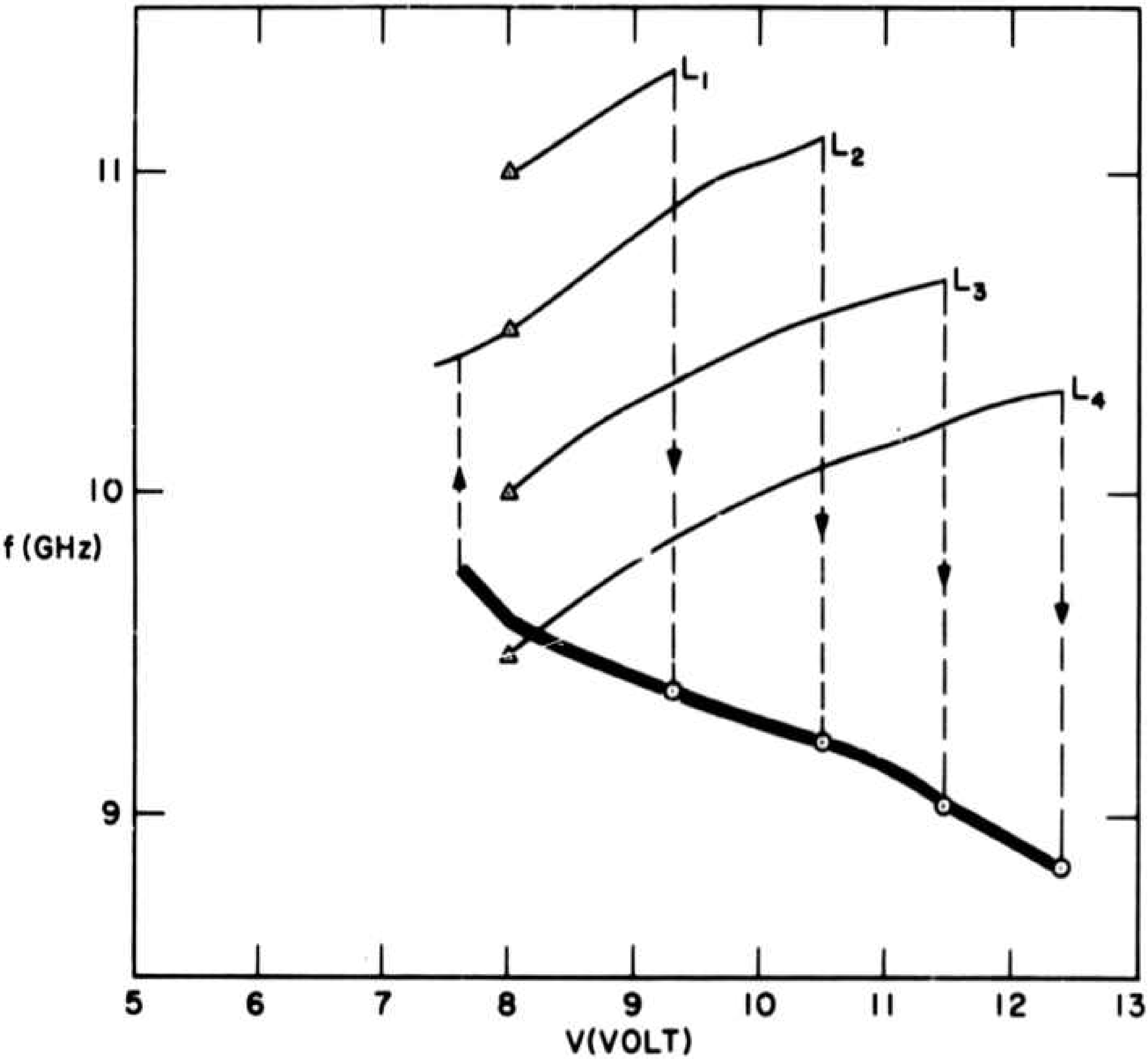

Figure 2. Typical voltage tuning curve.

lose cavity control of the device after a certain bias voltage which quite probably reflects as a decrease in the ratio of RF voltage to DC bias voltage. The tendency for this tuning behavior to occur decreases as the nl product is lowered and increases as the loading is increased.

I.2 Power Output

In designing a CW oscillator to perform reliably with long life (> 5000 hrs) one must consider the control of device temperature along with desired frequency, power, and impedance level. We have considered these factors in detail and have found that devices can be built to operate in the 4 to 13 GHz region with power output ranging into the hundreds of milliwatts. The higher power devices accordingly run hottest, but one can still fabricate them to operate under 170°C maximum temperature.

An example of a fairly high power device is given in Figure 3. We have plotted the output power at constant bias voltage for CW and pulsed operation. The maximum CW power shown is 140 mw at 7 GHz and at 11.0 V bias. Note that at 9.0 V bias the frequency response is better and is, at least in part, due to a lower input power and consequently a lower temperature rise (as indicated in the preceding section). The pulse power curve indicates the overall effect of temperature, and, as shown earlier, an enhanced output with respect to frequency is obtained. The device used in Figure 3 was 15.4 μm in length and was made from 0.5 Ω material with a dot contact diameter of 116 μm. The entire run of TE 240 devices was quite consistent although most maximum efficiency points were below 5% yet above

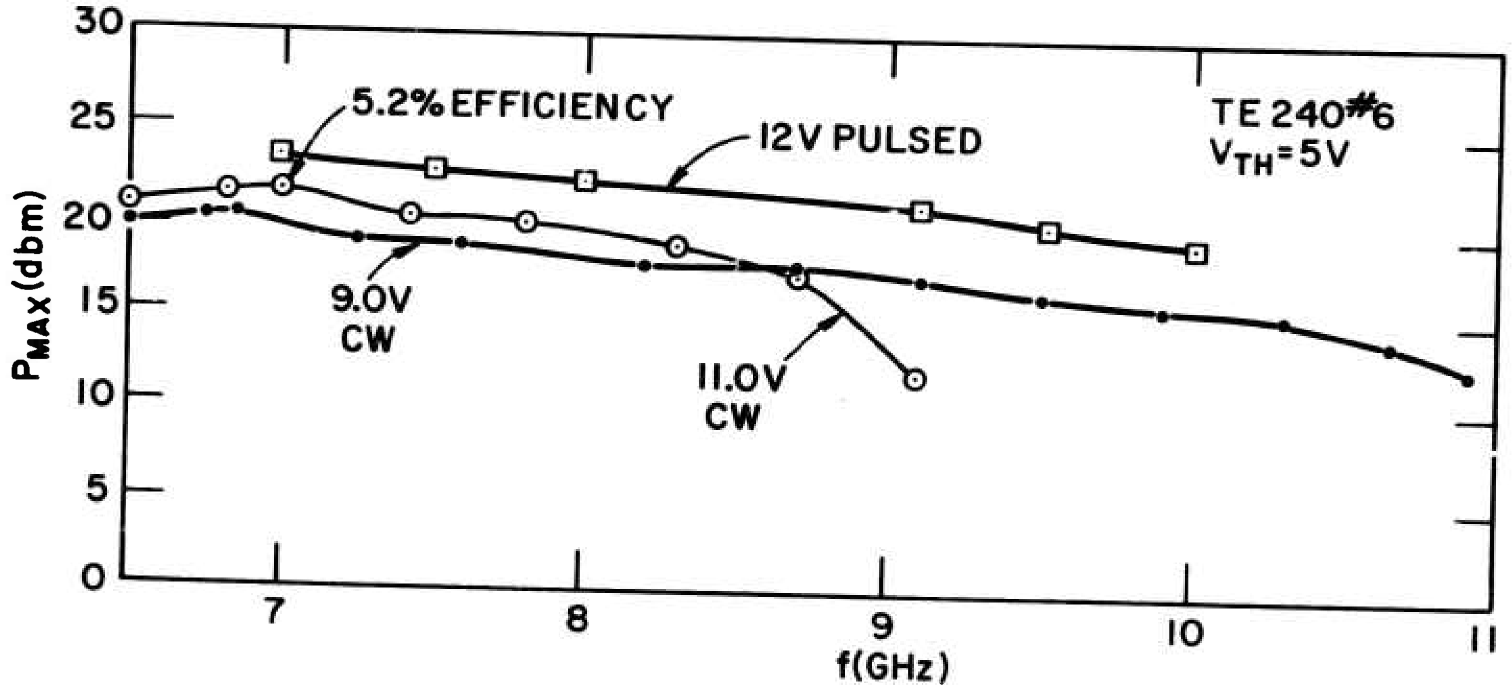

Figure 3. Pulsed and CW power output at fixed bias voltage.

4%. The power output for the TE 240's was flat within a few db from 8 GHz down to about 4 GHz.

To obtain good X-band operation, we must go to thinner devices. We have found that in order to push the CW power corner to the top end of X-band a device with 12 or 13 μm length is required. Such a device is shown in Figure 4 where again maximum power is plotted against frequency for a voltage of 9.4 V (twice threshold). The highest power is about 44 mw at 9 GHz with a 3 db drop at 11.6 GHz. Higher power has been obtained at the upper end of the frequency range, but the plot shown is fairly typical of a conservatively designed device for X-band operation. The efficiency for the TE 245 devices was about 3%. Similar runs have been made and efficiencies are 3% and better for all. We feel that our efficiency to date is still somewhat limited by our use of alloyed contacts but expect that the use in the near future of thin, grown n^+ skins will improve the efficiency considerably.

I.3 Noise Performance

We have shown in previous reports that the FM noise of our devices is consistently low and easily approaches that of the best available single cavity reflex klystrons. Figure 5 shows the FM noise spectrum of a TE 231 device compared to an HP 618A unlocked klystron signal source and a CV 2346 reflex klystron. When operated in a higher Q cavity, this same device will have lower noise and can be made to equal the CV 2346 noise level.

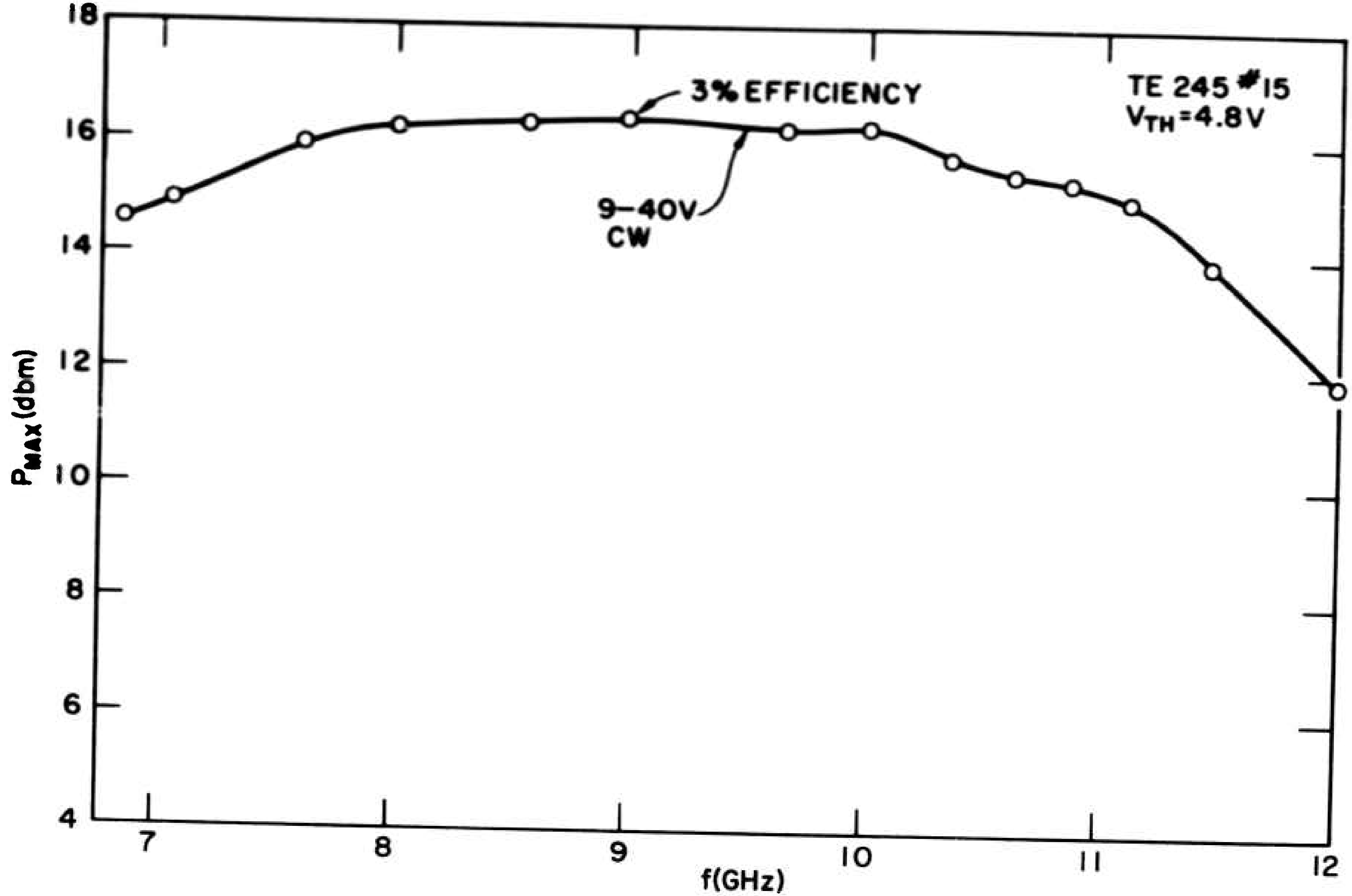

Figure 4. CW power output for X-band device.

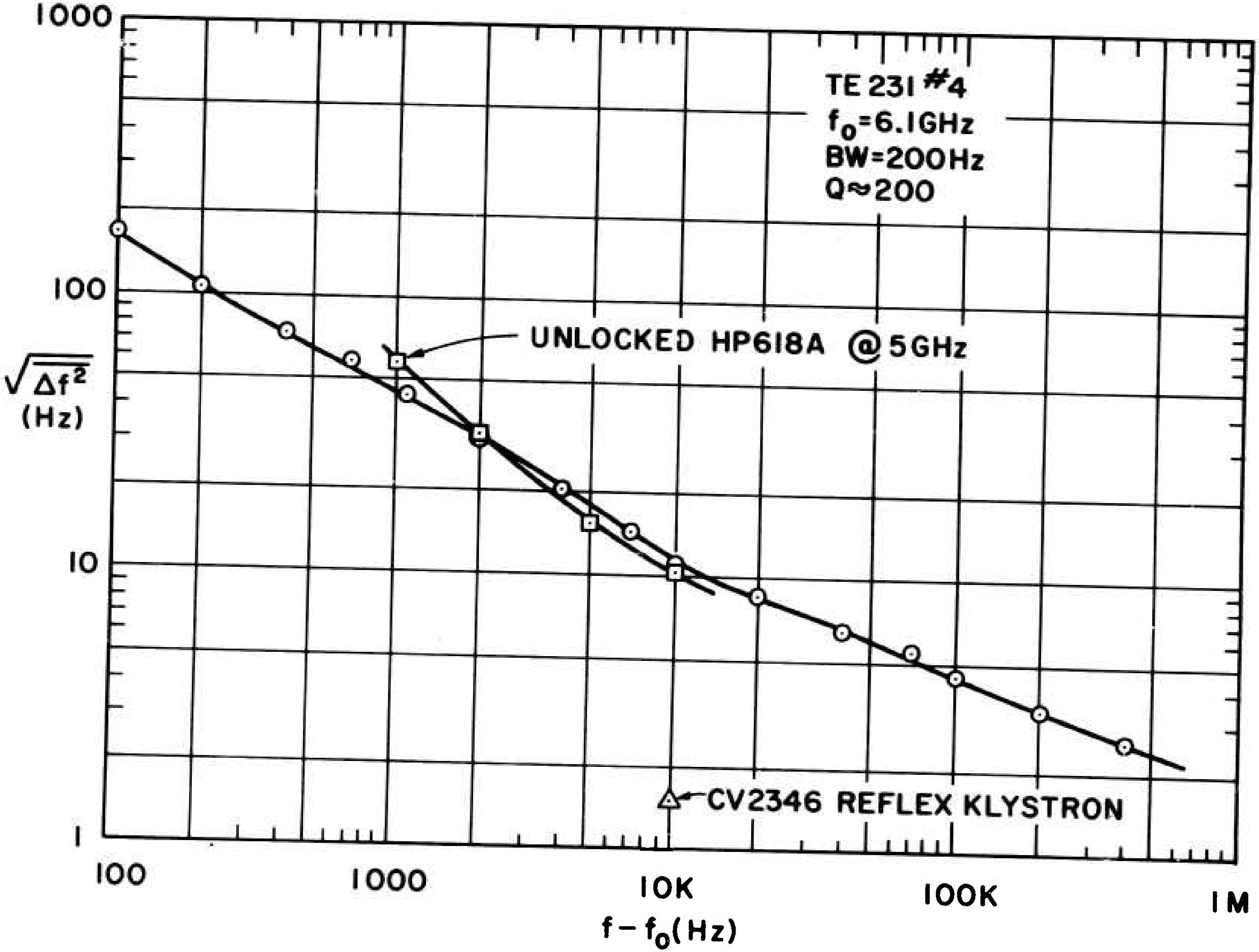

Figure 5. Gunn device and klystron noise spectra.

For X-band operation with medium Q values (≈ 200) the FM noise level is typically around 45 Hz at 10 KHz from the carrier in a 200 Hz bandwidth (≈ 50 db carrier power to noise power ratio) and can be as low as 10 to 15 Hz. In general, the noise levels for a given run are quite consistent but some variation does occur. We have found that a good qualitative correlation exists between the current noise and FM noise levels for otherwise identical devices. In a paper presented recently[1] we showed this noise behavior for TE 231-70 devices. Figures 6 and 7 reproduce some of the data presented and show what is a consistent trend for all our samples. In Figure 6 the FM spectra for samples #6 and #7 are given. Note that the devices are identical except that #7 has a higher noise level. In Figure 7 the current noise spectra are revealed for the two devices at both low and high field bias conditions. The noise levels are essentially the same for frequencies above 10 KHz where there appears to be a generation-recombination noise contribution. However, the 1/f noise component is quite a bit higher for sample #7. It is this "extra" 1/f noise that is quite probably responsible for the additional FM noise for sample #7. In any case, one will always find that the higher FM noise sample will have the highest low frequency current noise level.

[1] "Circuit and Noise Performance of Solution Grown Bulk GaAs Oscillators" by D. C. Hanson and J. S. Barrera, ICAMEB, Jan. 25, 1968, New York

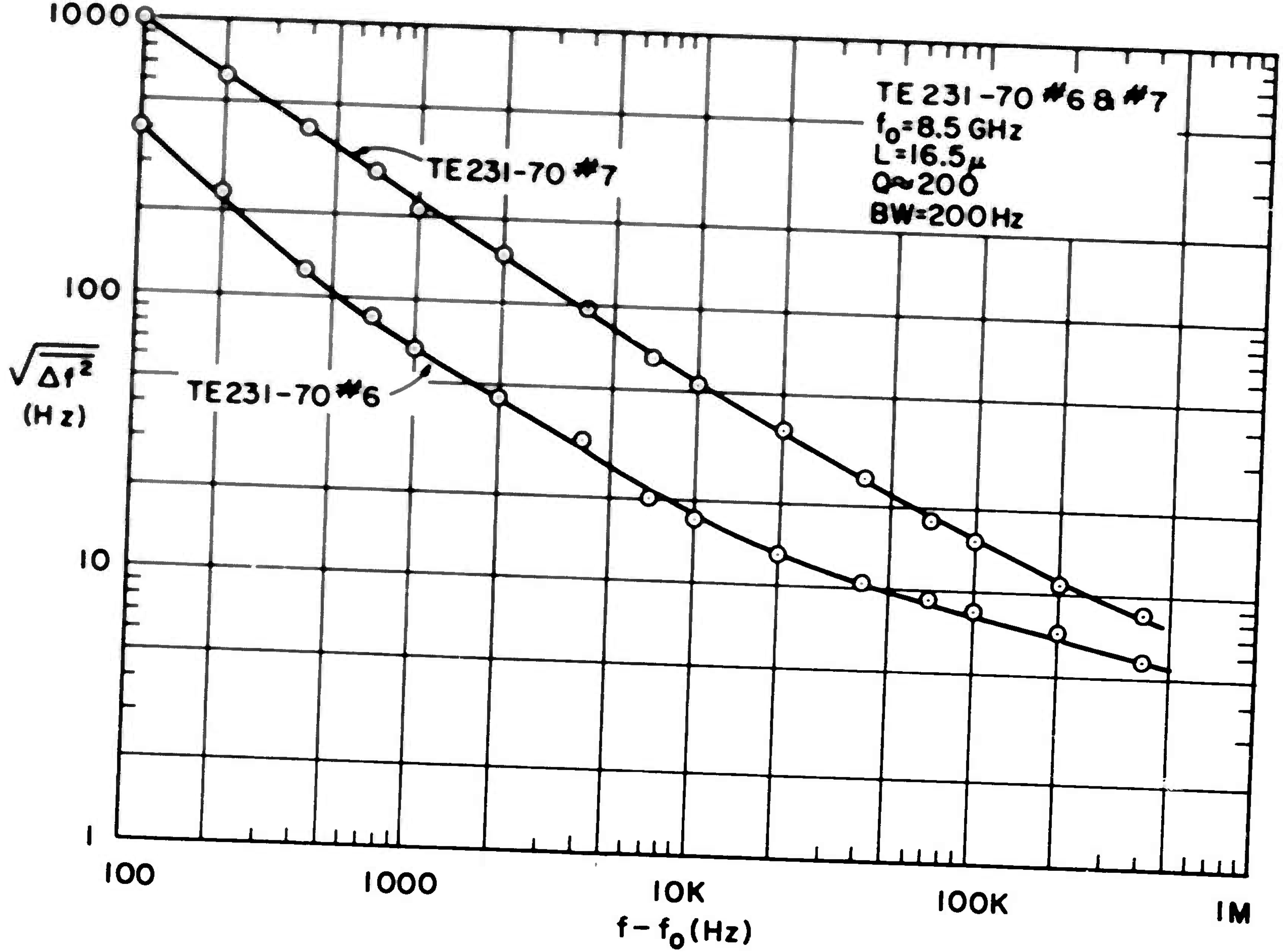

Figure 6. FM noise spectra of two "identical" devices.

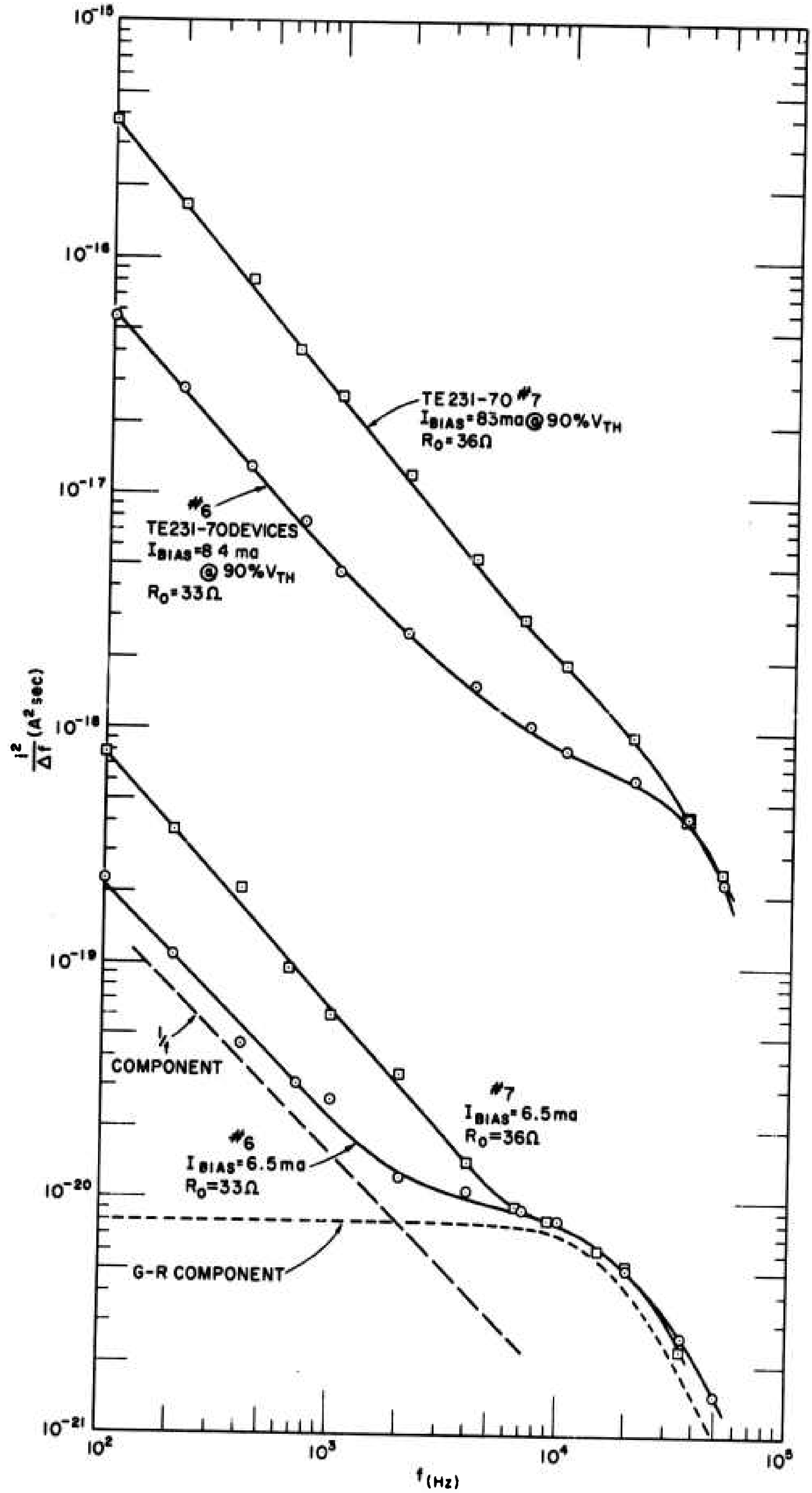

Figure 7. Current noise spectra of two "identical" devices.

II. PULSED GUNN EFFECT OSCILLATORS

II. 1 Specific Device Development

As a vehicle to demonstrate device capabilities, we plan to carry out the development of an actual device and to demonstrate its contributions in the specific area of solid state pulsed microwave sources for phased array microwave transmitter applications. Following are device goals and guidelines:

1. Application: phased array pulsed microwave transmitters.
2. Frequency range: C band with 5.675 GHz center frequency.
3. Tuning bandwidth: up to 10% of center frequency-voltage tuning.
4. Peak power output: 10 w or greater.
5. Duty factor: 1 to 5%.
6. Pulse duration: 0.1 to 10 microseconds.
7. Conversion efficiency: 15% or greater.
8. Output: 50 Ω line with an antenna load mismatch no greater than 4:1.

A coherent pulse output is required with phase preservation over hundreds of pulses. Design configuration, packaging, and circuitry is to be consistent with phased array module design with lateral extent less than λ cm.

II. 2 Device Considerations

After an appraisal of the technical guidelines of the preceding section, we intend that the major considerations involved for the device design should be as follows:

1. A rigorous study must be made of LSA operation versus Gunn or modified Gunn mode operation for producing efficient, pulsed, relatively high duty cycle power at C band frequencies.
2. Heat dissipation studies are required for even very high efficiency devices (> 15%), and geometry trade-offs between lateral and sandwich structures must be considered from both a heat dissipation and microwave operation standpoint.
3. From a circuitry viewpoint, cavity structures must be carefully designed to incorporate good heat sinking and trimmability to provide the exact frequency desired and overall size must, of course, be considered. Special attention must be paid to placement of the packaged device within the cavity--especially for LSA operation. Also very important are considerations of pulse bias circuitry for prevention of pulse degradation and suppression of low frequency bias oscillation.
4. It may prove necessary to rely on the use of multi-chip devices; that is, assuming problems of phase coherence do not occur for a multi-chip unit, then it is quite possible that

heat dissipation problems would become less severe and power demand per chip would become more reasonable.

5. Device characterization must be considered from the standpoint of statistical uniformity, reproducibility, and general parameter value stability. Besides careful monitoring of DC parameters, peak pulse powers and efficiencies, the measurement of pulse-to-pulse coherence and general phase coherence must be undertaken as a critical measurement.

II.3 Initial Device Development

At the time of writing of this report, the final fabrication and testing of the first run of pulsed devices has not been completed. We will report, however, on the initial device design and expected results.

Since all our previous work has dealt with a sandwich-type device with an evaporated dot contact on one side, we will try to transfer that experience gained over to a pulsed device design. From an average power standpoint, the thermal problem should be just as severe for the pulsed problem as it is for the CW situation. Considering the guideline requirements of 10 w at 15% efficiency and 5% duty cycle, we see that a dissipated power value of 3.33 w is the minimum wattage to be dealt with. This figure is just about the largest that we normally deal with for our CW devices to obtain relatively comfortable operation. Consequently, we shall set out to handle three watts average power as a starting point and will construct a sandwich-type device. We have found that a 15 to 17 μm device

will operate quite nicely at 5 to 6 GHz on a CW basis, and accordingly we will choose 16 μm as the active length of the device. Now, let

Input power at max bias = 3 watts avera

Efficiency = 5%

and consider a

Duty Factor = 5%

We then have,

Max Input Pulse Power = 60 watts

which leads to an expected peak output power of 3.0 watts.

For L = 16 μm, $V_{Threshold} \approx 5.2$ volts and if we make the assumption of operation around 5 V_{Th}, then we must have, for a maximum of 60 w peak input power, a bias current $I_{B_{Max}}$ of approximately 2.3 A. Now, the threshold current, I_{Th}, will be $\approx I_{B_{Max}}/.75$ or about 3 A assuming an average current drop of 25%. There is usually a current "bendover" at threshold bias such that the low field resistance R_o is $\approx 0.6\, V_{Th}/I_{Th}$. For this calculation then,

$$R_o \approx 0.6 \frac{5.2V}{3.0A} = 1.04\,\Omega .$$

Since $$R_o = \rho L/\pi r^2$$

we have

$$r = \sqrt{\frac{\rho L}{\pi R_o}}$$

or,

$$r = 2.26 \times 10^{-2} \sqrt{\rho} \text{ cm} .$$

For 0.1 Ω cm material our device will be 16 μm long and have a 143 μm dot diameter and for 5% efficiency should produce 3 watts peak power. Such a device will be fabricated and tested shortly.

II.4 Device Pulser

A duty cycle requirement of 5% for pulse widths around 1 μsec requires a pulser with high repetition rate capability. Our present HP 214A pulser is quite capable of providing the necessary bias pulse widths and at the desired repetition rates. However, for the 50 Ω output impedance ranges the maximum peak power available is about 40 w. We have thus considered the possibility of building a pulse amplifier to drive our devices using the HP 214A as the triggering pulser.

After checking the availability and performance of high power switching transistors, one quickly comes to the conclusion that there are virtually none that are fast enough for our requirements. Fortunately, however, there are available the relatively newly developed RCA overlay transistors. These units are not designed primarily as switches, but we found that they perform admirably, and we have, in fact, successfully developed a pulse source using two 2N5016's in parallel. On a CW basis

each transistor will carry 4.5 A collector current and will withstand up to 65 V collector-to-emitter voltage. The f_T is around 600 MHz.

Our circuit is very simple as can be seen in schematic form in Figure 8. Basically, we have an emitter follower with the two 2N5016's paralleled and with the GaAs device as the load. The 0.3 Ω emitter resistors are there to balance the transistors, and the 100 Ω input resistor tends to provide an ≈ 50 Ω input impedance to the HP 214A pulser when the expected device resistances are reflected to the input. Figure 9 shows a picture of the physical unit.

The available pulser output has not yet been fully explored, but some preliminary data is shown in Figures 10, 11, and 12. In Figure 10 we show the output voltage for a 10 A, 1 μsec pulse through a 2.5 Ω resistive load. The pulse is quite clean and is a conservative output for the circuit.

Figure 11 shows the output voltage across both a Gunn device and a resistor of the same low field resistance. The two waveforms are essentially indistinguishable. Figure 12 shows the voltage waveform for the above device on an expanded time scale. There is some ringing, but no attempt has yet been made to "clean-up" the circuit. The rise and fall times are actually less than what is shown due to the oscilloscope limitation.

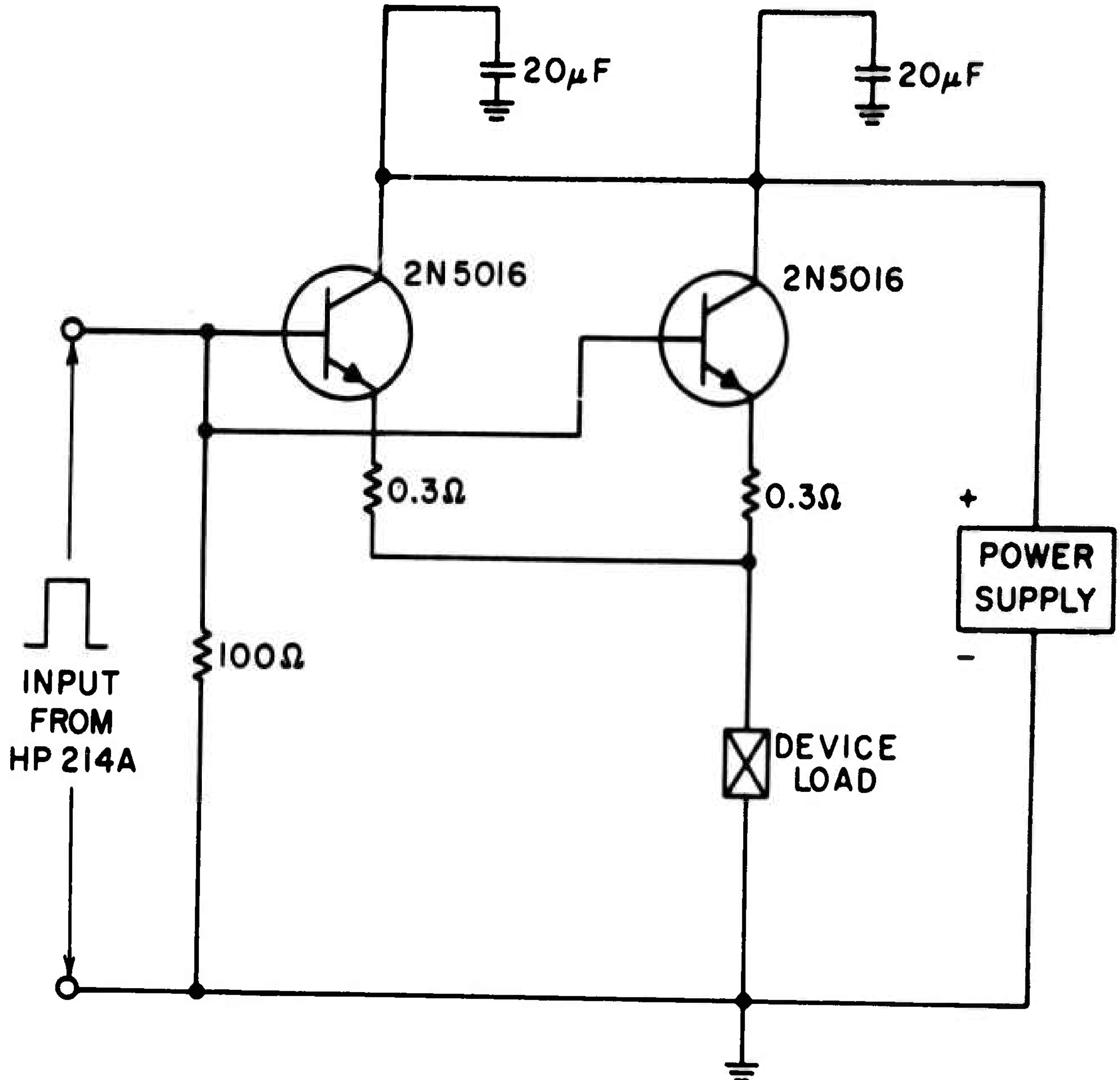

Figure 8. Pulser circuit schematic.

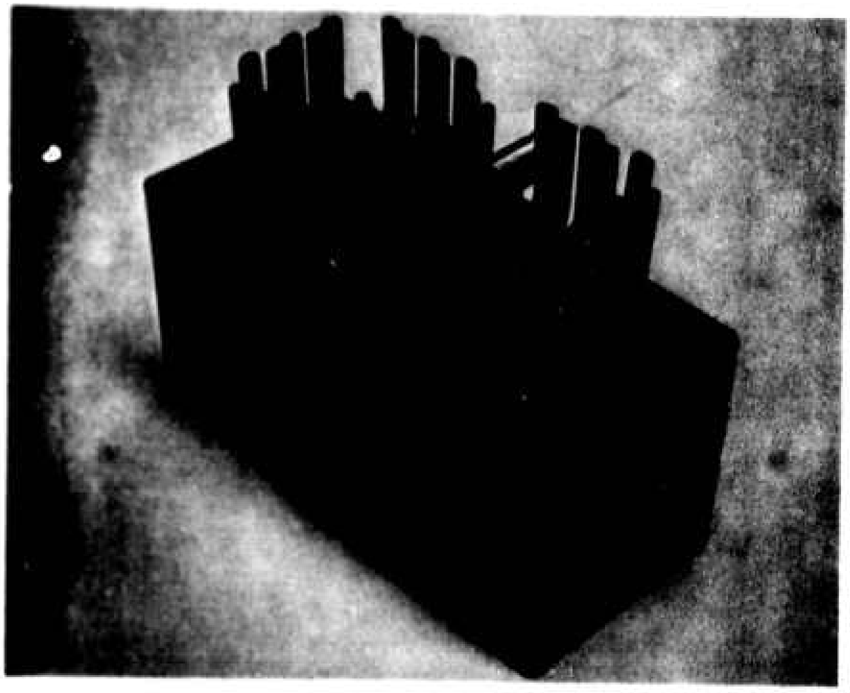

Figure 9. Transistor pulse amplifier.

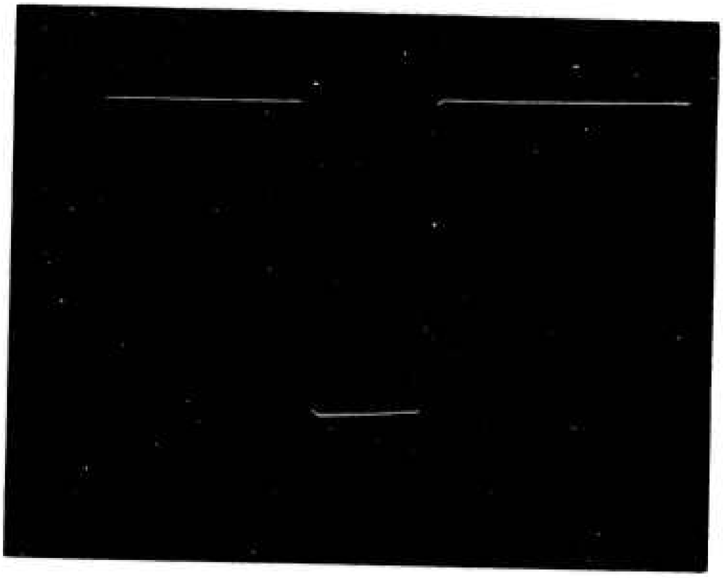

Figure 10. Pulse voltage across a 2.5 Ω resistor.

Vertical scale: 5 V/cm

Horizontal scale: 0.5 μsec/cm

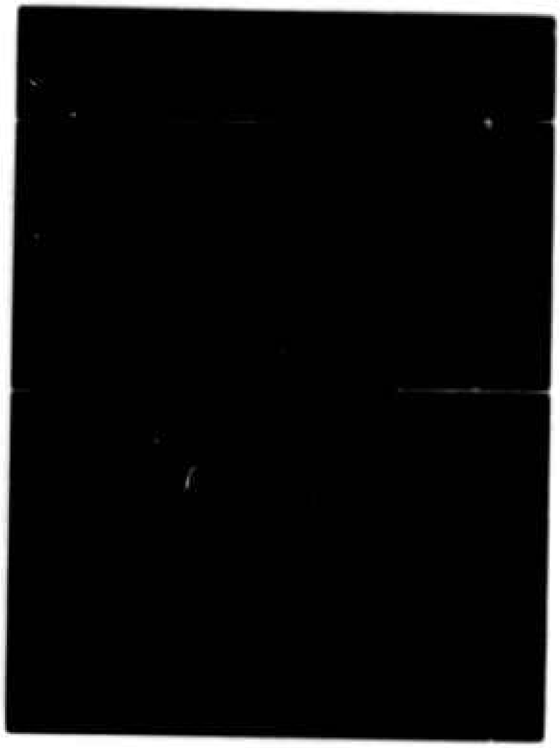

Figure 11. Pulse voltage across a Gunn effect device (bottom) and resistor of equal low field value.

Vertical scale: 5 V/cm

Horizontal scale: 0.5 μsec/cm

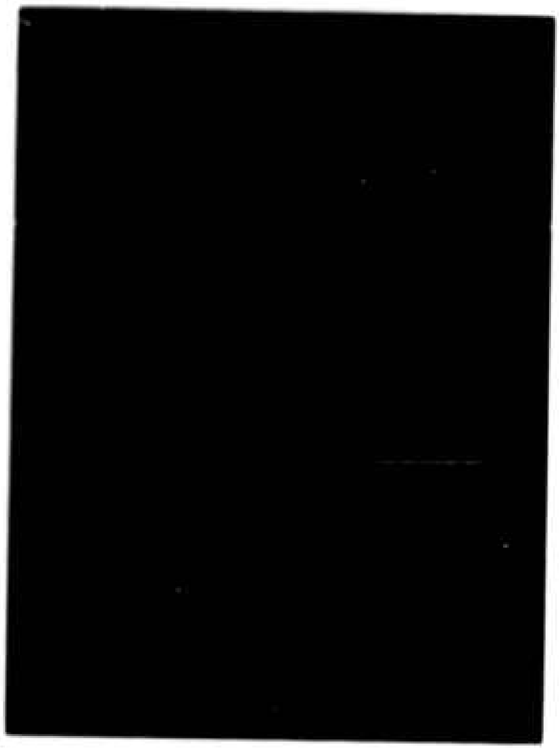

Figure 12. Pulse voltage across Gunn effective device.

Vertical scale: 5 V/cm

Horizontal scale: 50 nsec/cm

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13. ABSTRACT

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Gunn Effect Devices 4						
Power and Noise Performance 4						
Pulsed Device Design 3						
Pulser Circuit Design 3						

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